Core excited states in the $A=51$ mirror nuclei

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(Received 9 August 2004; published 18 November 2004)

Three previously unknown high-energy $\gamma$-ray transitions between 4.2 and 5.4 MeV were identified in the $T_z=-1/2$ nucleus $^{51}$Fe following the fusion-evaporation reaction $^{32}$S($^{28}$Si,2$n$1$n$)$^{51}$Fe. These transitions represent decays of core excited states. The $\gamma$ rays were detected in the Ge detector array Gammasphere combined with the neutron detector system Neutron Shell and the charged-particle array Microball. The three transitions are related to the mirror transitions in the $T_z=+1/2$ nucleus $^{51}$Mn, and the resulting mirror-energy difference diagram is discussed with predictions from large-scale shell-model calculations.

DOI: 10.1103/PhysRevC.70.057305 PACS number(s): 21.60.Cs, 23.20.En, 23.20.Lv, 27.40.+z

The concept of isospin symmetry in nuclear physics relies on the assumptions that the nuclear force is charge symmetric and charge independent. This implies that the proton and neutron can be described as two different states of the same particle—the nucleon—characterized by the isospin quantum number $T_z$. However, isospin nonconserving components of the nucleon-nucleon interaction, with the Coulomb interaction between the protons being the most important, clearly break the isospin symmetry. The resulting effects can be studied in mirror nuclei, which are pairs of nuclei having the number of protons and neutrons interchanged.

Since the $1f_{7/2}$ shell is relatively isolated in energy, a large fraction of $1f_{7/2}$ configurations in the resulting wave functions of nuclear states of $N\sim Z$ and $A\sim 50$ nuclei can be expected. The effects of isospin-symmetry breaking in these nuclei is thus relatively easy to interpret, because modern large-scale $fp$ shell-model calculations provide high-quality wave functions. Mirror nuclei in the $1f_{7/2}$ shell have been studied in detail during recent years [1–8]. Accompanying theoretical efforts have been undertaken to explain mirror-energy difference diagrams of mirror nuclei in detail. Very recently, a description has been suggested, which includes an isospin-symmetry breaking component in the nuclear interaction [9]. However, these studies have so far only focused on states with $1f_{7/2}$ configurations as a leading component in their wave functions. In this work we present results on excited states in the $T_z=-1/2$ nucleus $^{51}$Fe, which are built on particle-hole excitations across the shell gaps at particle numbers $N=Z=28$. A comparison with the $T_z=+1/2$ mirror partner $^{51}$Mn allows, for the first time, for a mirror-symmetry investigation of this class of states.

The present work is based on data from two experiments as described in more detail in e.g., Refs. [10,11]. Both experiments employed the fusion-evaporation reaction $^{32}$S+$^{28}$Si at 130 MeV beam energy. Enriched 0.5 mg/cm$^2$ $^{28}$Si targets supported with either 1 mg/cm$^2$ Ta or Au foils facing the beam were used. The $\gamma$ rays were detected in the Gammasphere array [12,13], which comprised 78 Ge detectors with the Heavimet collimators removed. For the detection of light charged particles the $4\pi$ CsI-array Microball [14] was used. The Neutron Shell [15], consisting of 30 liquid-scintillator detectors, replaced the five most forward rings of Gammasphere to enable the detection of evaporated neutrons. This allows for the study of weak reaction channels at and beyond the $N=Z$ line.

The reaction leads to the $A=51$ mirror nuclei $^{51}$Fe and $^{51}$Mn following the evaporation of two $\alpha$ particles and one neutron, and two $\alpha$ particles and one proton, respectively. The relative experimental fusion-evaporation cross section of $^{51}$Mn amounts to $\sim 18\%$, while the relative cross section of $^{51}$Fe is only $\sim 0.07\%$.

The $\gamma$-ray events were selected by appropriate conditions on the number of and kind of evaporated particles and incremented into various $E_\gamma$ projections and $E_\gamma-E_\gamma$ matrices. To improve the $\gamma$-ray energy resolution an event-by-event kine-
TABLE I. Energies of core excited states in 51Fe and 51Mn [11], transition energies, relative intensities, angular distribution ratios, and experimental and calculated mixing ratios of γ rays, experimental and calculated MED values of initial states, and the spins and parities of the initial and final states.

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<td>11468(7)</td>
<td>4199(6)</td>
<td>2.0(5)</td>
<td>0.4(2)</td>
<td>&gt;0.2</td>
<td>1.98</td>
<td>-42(8)</td>
<td>-116</td>
<td>-180</td>
<td>(29/2)</td>
<td>27/2</td>
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<td>4443(13)</td>
<td>0.5(5)</td>
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<td></td>
<td>0.42</td>
<td>-69(15)</td>
<td>-21</td>
<td>26</td>
<td>(29/2)</td>
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<td>12650(11)</td>
<td>5381(10)</td>
<td>1.0(5)</td>
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<td>-141(11)</td>
<td>-92</td>
<td>-155</td>
<td>(31/2)</td>
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<td>51Mn</td>
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<td>11509.9(11)</td>
<td>4336.4(15)</td>
<td>4.3(4)</td>
<td>1.58(8)</td>
<td>-0.51(35)</td>
<td>-2.29(45)</td>
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<td>29/2</td>
<td>27/2</td>
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<tr>
<td>11781.1(11)</td>
<td>4605.8(15)</td>
<td>3.3(4)</td>
<td>0.55(4)</td>
<td>0.35(11)</td>
<td>2.05(10)</td>
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<td>27/2</td>
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<tr>
<td>12791.4(11)</td>
<td>5617.2(18)</td>
<td>5.8(6)</td>
<td>1.49(7)</td>
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<td></td>
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<td>31/2</td>
<td>27/2</td>
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mastic reconstruction method was used to reduce the effect of the Doppler broadening caused by the evaporated particles.

To separate events where the T₁/2 nucleus 51Fe was populated at relatively high angular momenta and excitation energies, additional restrictions were applied on the sum of the two α-particle energies and the total detected γ-ray fold. Only events in 51Fe having summed α-particle energies less than 27 MeV and with a detected total γ-ray fold higher than five were considered, which is a compromise between statistics and a low background level.

Multipolarity assignments of transitions are based on ratios of yields R₁₄₁−₉₇, which is the ratio of γ-ray intensities measured at the backward section of the Gammasphere (average angle θ = 141° with respect to the beam axis) versus the central section of the Gammasphere (θ = 97°) [16]. Table I shows R₁₄₁−₉₇ together with level energies, γ-ray transition energies, relative γ-ray intensities, and spins and parities of initial and final states for the core excited states in the A = 51 mirror nuclei.

Figure 1(a) shows a spectrum obtained from a γγ matrix in coincidence with two α particles and one proton by gating on the 27/2⁻ → 23/2⁻ 704 keV transition in 51Mn. The apparent peaks in the spectrum represent transitions belonging to the well-known low-energy structure in 51Mn (cf. Ref [11] and references therein). The corresponding transitions are included in Fig. 2(b), which shows the relevant part of the 51Mn level scheme [11]. The inset of Fig. 1(a) focuses on the high-energy portion of the spectrum. Several transitions (and associated single-escape peaks) are clearly seen at 4336, 4606, 5010, 5258, and 5617 keV. They represent previously known high-energy transitions connecting core excited 29/2⁻ and 31/2⁻ states to the yrast 27/2⁻ state in 51Mn at 7176 keV excitation energy [11].

Figures 1(b)–1(d) show spectra deduced from a γγ matrix in coincidence with two α particles and one neutron. In addition, the above-mentioned restrictions on the sum α-particle energy and total γ-ray fold are applied. The sum spectrum in Fig. 1(b) is in coincidence with several strong transitions in 51Fe below the yrast 27/2⁻ state at 7269 keV. These are seen in Fig. 2(a), which shows the level scheme of 51Fe deduced from previous work [3, 4] and the present study. The lines in Fig. 1(b) represent these transitions in the yrast structure. In the inset of Fig. 1(b) the high-energy part of the spectrum is shown where peaks at 4199, 4443 (tentatively), and 5381 keV are visible. Figures 1(c) and 1(d) are the spectra obtained after requiring a coincidence with the 4199 and 5381 keV transitions, respectively. Coincidences with several transitions below the 27/2⁻ state, including the 27/2⁻ → 23/2⁻ 777 keV transition, are seen.

Comparing the high-energy insets of Figs. 1(a) and 1(b) in terms of intensity relations and using mirror symmetry arguments, it seems natural to view the 4199, 4443, and 5381 keV transitions in 51Fe as mirror transitions to the 4336, 4606, and 5617 keV transitions in 51Mn, respectively. This allows for the tentative assignments Jₚ = (29/2), (29/2), and (31/2) for the states at 11468, 11712, and 12650 keV in 51Fe, respectively, as the spins and parities of the corresponding states in 51Mn are well established [11]. Moreover, despite the low statistics a multipolarity assignment for the 4199 keV transition can be made. The R₁₄₁−₉₇ value of 0.42 indicates a mixed E2/M1 transition with a significantly large and positive mixing ratio, δ(E2/M1) [11], which establishes the spin assignment suggested previously from mirror symmetry arguments. For the 4443 and 5381 keV transitions meaningful measurements of R₁₄₁−₉₇ were not possible due to insufficient statistics.

The observed γ rays together with the core excited states in 51Fe are included in Fig. 2(a). Comparing this level scheme with the well known level scheme for 51Mn displayed in Fig. 2(b), a mirror-energy difference (MED) diagram can be derived and the latter is shown in Fig. 2(c). The open squares up to spin J = 27/2 represent previously known experimental data [3,4], whereas the data points for J = 29/2 and J = 31/2 denote the new information arising from the yrast core excited states. The MED decreases rapidly from the fully aligned J = 27/2 states, which are based on a single 1f₇/2 configuration (~70%), to the core excited states.

To interpret the experimental MED diagram large-scale shell-model calculations were performed using the shell-model code ANTOINE [17, 18]. The calculations were performed using the KB3G with Coulomb interaction [19] in the full fp space containing the 1f₇/2 orbit below and the 2p₃/2,
the calculations: inequivalent single-particle energies for neutrons and protons with values 0.0, 2.0, 4.0, and 6.5 MeV for the $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbits, respectively and (ii) different neutron (0.0, 2.0, 4.0, and 6.5 MeV) and proton (0.0, 1.8, 3.8, and 6.5 MeV) single-particle energies. In the calculations bare $g$ factors and effective charges of 1.5e for protons and 0.5e for neutrons were used. Experimental $\gamma$-ray energies and calculated transitions matrix elements were used to derive mixing ratios of transitions.

The calculations of MED values follow a procedure suggested and discussed in detail in Ref [9]. In that work the MED is expanded in a monopole Coulomb (CM), a multipole Coulomb (CM), and an isospin breaking nuclear interaction component (B) according to

$$\text{MED}_J = \Delta\langle V_{\text{CM}}\rangle_J + \Delta\langle V_{\text{CM}}\rangle_J + \Delta\langle V_{B}\rangle_J. \quad (1)$$

In the expression above $\Delta\langle V\rangle_J$ should be interpreted as a difference in expectation values of $V$ between the $T_z = -1/2$ partner and $T_z = +1/2$ partner at angular momentum $J$. The $V_{\text{CM}}$ term is essentially the stored Coulomb energy. Following the arguments in Ref. [9], $V_{\text{CM}}$ depends on differences in proton plus neutron $2p_{3/2}$ occupation numbers. $V_{\text{CM}}$ is accounted for by using the harmonic oscillator Coulomb matrix elements (CME) and $V_B$ is taken into account by adding 100 keV to the $J=2 f_{7/2}$ CME, corresponding to the discrepancy between the observed $J=2$ MED value in the $A=42$ mirror nuclei and the normalized $J=2$ CME. The effect of $V_{\text{CM}}$ and $V_B$ following the calculations are thus resulting from diagonalization rather than perturbation as indicated in Eq. (1). However, it can be shown that the two approaches give more or less identical results. Using equivalent single-particle energies for neutrons and protons the results shown in Table I are labeled MED$_{\text{th1}}$ and included in Fig. 2(c) as filled circles.

The $J=29/2$ and $J=31/2$ MED values were also interpreted using a slightly different approach. The $V_{\text{CM}}$ term as described above is disregarded and instead different single-particle energies for protons and neutrons, deduced from the single-particle spectra of the $A=41$ mirror nuclei $^{41}\text{Ca}$ and $^{43}\text{Sc}$, are used. This also represents a monopole Coulomb effect, but which instead is proportional to differences in proton minus neutron $2p_{3/2}$ occupation numbers. Since the yrast core-excited states are of single-particle nature [11] the motivation for using different single-particle energies in the calculation is obvious. The results are labeled MED$_{\text{th2}}$ in the table and correspond to the filled diamonds in Fig 2(c).

The two calculations give rather similar results, but the overall agreement with experiment is not perfect for either of them. While the agreement for the $J=31/2$ states is good in the latter calculation, the first calculation does somewhat better for the yrast $J=29/2$ states. Thus, although the monopole Coulomb part seems to be decisive for explaining the observed MED values, it is not clear which of the two approaches (or a combination of them) should be used.

The mixing ratios, $\delta(E2/M1)$, were also calculated for the high-energy dipole transitions depopulating the core excited states (see Table I). For comparison the experimental mixing ratios, when available, are also given. In $^{51}\text{Fe}$ the calculated mixing ratios are positive and the value for the $29/2^+ \rightarrow 27/2^+$ transition, $\delta_{\text{th}}=1.98$, is consistent with $K_{141-83} = 0.4(2)$, from which we conclude $\delta > 0.2$. The calculated mixing ratios in $^{51}\text{Mn}$ are negative and in agreement with the
The experimental value for the $29/2^-\rightarrow 27/2^-$ transition but in contradiction with the experimental value for the $29/2^+\rightarrow 27/2^+$ transition. The change of signs in mixing ratios in the mirror pair is due to a change of signs in the reduced $M1$ transition probabilities and reflects the single-particle character of these transitions.

In summary, three previously unknown core excited states were found in the $T_z=-1/2$ nucleus $^{51}\text{Fe}$. The states decay through high-energy transitions to the yrast $27/2^-$ state. A comparison with the $T_z=+1/2$ mirror partner $^{51}\text{Mn}$ reveals negative MED values for these states. The trend is reproduced by large-scale shell-model calculations. However, for a detailed discussion more experimental cases are necessary.

We would like to thank the accelerator crews and the Gammasphere support staff at Argonne and Berkeley for their supreme efforts. The target maker, Jette Agnete Sørensen, at the Niels Bohr Institute, Copenhagen, Denmark, is also greatly acknowledged. This work is supported in part by the Swedish Natural Science Research Councils and the U.S. Department of Energy under Grant Nos. DE-AC03-76SF00098 (LBNL), DE-FG05-88ER-40406 (WU), and W-31-109-ENG38 (ANL).